CONCEPTUAL DESIGN AND ANALYSIS OF SERVICE ORIENTED ARCHITECTURE (SOA) FOR COMMAND AND CONTROL OF SPACE ASSETS

THESIS

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Abstract

The mission-unique model that has dominated the DoD satellite Command and Control community is costly and inefficient. It requires repeatedly "reinventing" established common C2 components for each program, unnecessarily inflating budgets and delivery schedules. The effective utilization of standards is scarce, and proprietary, non-open solutions are commonplace. IT professionals have trumpeted Service Oriented Architectures (SOAs) as the solution to large enterprise situations where multiple, functionally redundant but non-compatible information systems create large recurring development, test, maintenance, and tech refresh costs. This thesis describes the current state of Service Oriented Architectures as related to satellite operations and presents a functional analysis used to classify a set of generic C2 services. By assessing the candidate services' suitability through a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, several C2 functionalities are shown to be more ready than others to be presented as services in the short term. Lastly, key enablers are identified, pinpointing the necessary steps for a full and complete transition from the paradigm of costly mission-unique implementations to the common, interoperable, and reusable space C2 SOA called for by DoD senior leaders.

Acknowledgments

I owe a sincere debt of thanks to my faculty advisor, Dr. John Colombi, for his guidance and support. Throughout the course of this thesis effort I dealt with topic changes, a deployment, gaps in my knowledge, and run-of-the-mill writer's block. Through it all I depended on Dr. Colombi for honest, sage advice on how best to proceed. Although I know this effort took me longer to complete than he would have preferred, I am just as certain it would not be finished at all if it were not for the experience, wisdom, and motivation he provided me on an ongoing basis.

My wife Natalie also tolerated many hours without me as I wrote in front of the computer. As has been true about so many other aspects of our life together, her patience and support were invaluable to me finishing this thesis.

--Eric Snyder

Table of Contents

Page

List of Figures

List of Tables

Page

CONCEPTUAL DESIGN AND ANALYSIS OF SERVICE ORIENTED ARCHITECTURE (SOA) FOR COMMAND AND CONTROL OF SPACE ASSETS

I. Introduction

Background

A significant and continuing challenge confronting the defense space acquisition community is the large cost of developing, testing, deploying, and operating space systems. The complexity of the myriad boosters, spacecraft buses, and payloads drives much of this cost. The potentially catastrophic results of failure in the space domain contribute to a highly risk averse culture, further increasing costs through extreme deliberateness and cumbersome mission assurance efforts. In contrast to the aforementioned areas, however, the command and control (C2) structures for space systems typically rely on conventional information technologies that entail less impactful risks should defects surface during on-orbit operations. It is surprising, then, that satellite mission ground segments have suffered from similar developmental and fielding woes to space segments in terms of out-of-control cost growth and schedule delays (1).

IT professionals have trumpeted Service Oriented Architectures (SOAs) as the solution to large enterprise situations where multiple, functionally redundant but non-compatible information systems create large recurring development, test, maintenance, and tech refresh costs. Through the abstraction of platform-specific applications into generic services, the combination and re-use of these services becomes possible,

ultimately saving repeatedly incurred costs that deliver no value-added functionality. In addition, SOAs have been praised for their emphasis on separating “business logic” from the arcane details of a particular programming language or coding approach, enabling system flexibility to changing market conditions or business practices.

Service Oriented Architectures are built around the following tenets:

- Discoverable services treated as black boxes
- Well-defined standards for system/service interfaces and for data definitions
- Loose coupling (minimized dependencies between software components)
- Deliberate code separation between the “business logic” and “software logic” of each component service, allowing flexibility and adaptability in mission execution.

Problem Statement

The boutique, one-off production model that has dominated the space C2 community is costly and inefficient. It requires repeatedly “reinventing the wheel” in order to achieve mission success. The effective utilization of standards is scarce, and proprietary, non-open solutions are commonplace. In a budget constrained environment and on a wartime footing where Joint Force Commanders are demanding space capabilities on a much more responsive basis, the space acquisition community must identify a new model to deliver effective, maintainable, and extensible satellite C2 systems both faster and cheaper than the current paradigm.

Research Objectives/ Questions

This thesis has two primary objectives:

1. Understand the current state of Service Oriented Architectures (SOA) in satellite C2 systems either in current operational use, in commercial development, or proposed architectures by commercial and government entities
2. Identify and assess a list of common services to be used in a generic satellite C2 SOA. Show the notional interactions and relationships between these services using DoDAF version 2 service views.

In order to achieve these objectives, the following questions will scope and guide the effort.

1. What services are suitable for a space C2 SOA implementation?
2. How can a set of proposed Space C2 services be assessed for future acquisition?

Hypotheses

Applied to the satellite C2 domain: SOAs can offer these major benefits:

- Re-use of existing common services and data definitions across the space C2 enterprise, regardless of mission type or platform (positioning/navigation, communications, surveillance, weather, space warning, space control, etc.), leading to drastic improvements in cost and schedule
- The ability for C2 systems to evolve gracefully over time. Technology refreshment, hardware replacement, and software upgrades can be executed more quickly and with less cost and risk because of standardized interfaces and minimized dependencies between services. Additionally, satellite C2 systems

built as SOAs should have the ability to readily adapt to changes in mission taskings, governing regulations/policies, or organizational interfaces.

- The ability to leverage web services to deliver federated security management across traditional network boundaries of like classification, allowing efficient information transfer to individuals and organizations with verified credentials
- Improved interoperability with other DoD and coalition partner systems, better enabling net-centricity across the force.

Methodology

To identify candidate satellite C2 services, the methodology specified in the DoDAF, Volume 2 will be used as a guide. Once a set of services is proposed, an evaluation matrix will be utilized to assess each service against a set of criteria comprising the widely-accepted key organizational and technical benefits of implementing a SOA. Analyzing the proposed services in this way will illustrate whether or not there is an advantage to presenting satellite C2 functionality as services, as opposed to the current model of mission-unique implementations.

Assumptions/Limitations

This thesis examines service orientation as an organizing principle for designing a cost-effective and operationally responsive enterprise-level satellite C2 architecture. The analyses contained are primarily functional in nature, and as such, the technical service

design (enterprise service buses, registries, interface definitions etc.) will be left to others to design and assess performance.

Implications

Lack of responsiveness to identified needs is perhaps the single most important issue facing the military space community. In many cases proven technology exists to meet an urgent Joint Force Commander (JFC) need. However, high costs and lengthy fielding timelines nevertheless leave the warfighter waiting unacceptably long for required capabilities. Service Oriented Architectures, through their reliance on accepted standards, their inherent adaptability to various missions, and their vast potential for re-use can help alleviate the issue of responsiveness in space. If satellite C2 development is not needlessly reinvented with every new mission, cost and schedule control can be gained, focusing on the true challenges associated with a given acquisition, thereby allowing the needed capability to be delivered sooner.

II. Literature Review

Chapter Overview

The literature review chapter in this thesis is intended to provide an analysis of the current state of Service Oriented Architectures and their potential application to satellite command and control implementations. Initially, it will examine scholarly writings on SOAs in general, authored by information technology professionals and leading researchers in the field. Further, guidance issued from Department of Defense and US Air Force senior leadership will be assessed to determine what governance exists regarding SOA concepts and the associated implications on current or future development efforts. Finally, it will investigate the writings and conference proceedings of a variety of satellite C2 experts in the civil, defense, and commercial sectors at the technical, managerial, and executive levels, capturing their viewpoints on the potential benefits and challenges of implementing SOA in satellite ground segments.

The Rise of SOA (DCOM, CORBA, and Web Services)

SOA evolved in the late 1990s and early 2000s from DCOM (Distributed Component Object Model) and CORBA (Common Object Request Broker Architecture), two distributed architectures aiming to standardize and simplify messaging between software applications (termed objects under the object-oriented model) by establishing common interface schemas (2). DCOM was introduced in 1996 and works primarily with Microsoft Windows (3). It was used in applications such as the Microsoft Office family of products. DCOM failed in two areas. Although it has been ported to other

platforms, it has achieved broach reach only on the Windows platform (4) Furthermore, DCOM applications are difficult to deploy in an environment where communications must be performed across firewalls (4).

CORBA also grew out of the object orientation model, with v1.0 released by the prolific Object Management Group (OMG) in 1991. 1.0 was not interoperable and provided only a C mapping, so the OMG (Object Management Group) published CORBA 2.0 in 1997. It provided a standardized protocol and a C++ language mapping, with a Java language mapping following in 1998. This gave developers a tool that allowed them to build heterogeneous distributed applications with relative ease. CORBA rapidly gained popularity and quite a number of mission-critical applications were built with the technology. The most obvious technical problem with CORBA is its complexity—specifically, the complexity of its APIs. Many of CORBA's APIs are far larger than necessary. For example, CORBA's object adapter requires more than 200 lines of interface definitions, even though the same functionality can be provided in about 30 lines—the other 170 lines contribute nothing to functionality, but severely complicate program interactions with the CORBA runtime. Unfortunately, due to the myriad IDL mappings required, CORBA implementations could become very complicated (5).   In a near mirrored result to that of DCOM, CORBA was never adopted by Microsoft Corporation, and therefore never gained universal acceptance within the industry (though it was and is still widely used).

Remote Procedure Call (RPC) technologies like DCOM and CORBA faced issues involving resources and persistent connections. Adding to this was an increased maintenance effort resulting from the introduction of the middleware layer. Upon the arrival of the World Wide Web, HyperText Transport Protocols (HTTP) in conjunction with the Internet Browser replaced proprietary RPC protocols used to communicate between the user's workstation and server (6). These distributed Internet architectures were known as "web services." Web Services became the genesis for Service Oriented Architecture in the sense that they provided universally accepted means for web applications to have standard interface definitions and communicate with other applications not otherwise a priori designed to work together.

The World Wide Web Consortium (abbreviated W3C, the main international standards organization for the internet) defines a web service as a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-readable format (specifically Web Services Description Language, or WSDL). Other systems interact with the web service in a manner prescribed by its WSDL description, with messages often formatted using a SOAP (Simple Object Access Protocol) vocabulary, typically conveyed using HTTP with an eXtensible Markup Language (XML) serialization (7). Web Services often utilize a service registry acting as a directory where services can be discovered, described, and the appropriate WSDL interface fully defined. These service registries or brokers will typically comply with the Universal Description, Discovery, and Integration (UDDI)

specification (6 p. 253). Figure 1 depicts the typical data flow and protocols associated with Web Services.

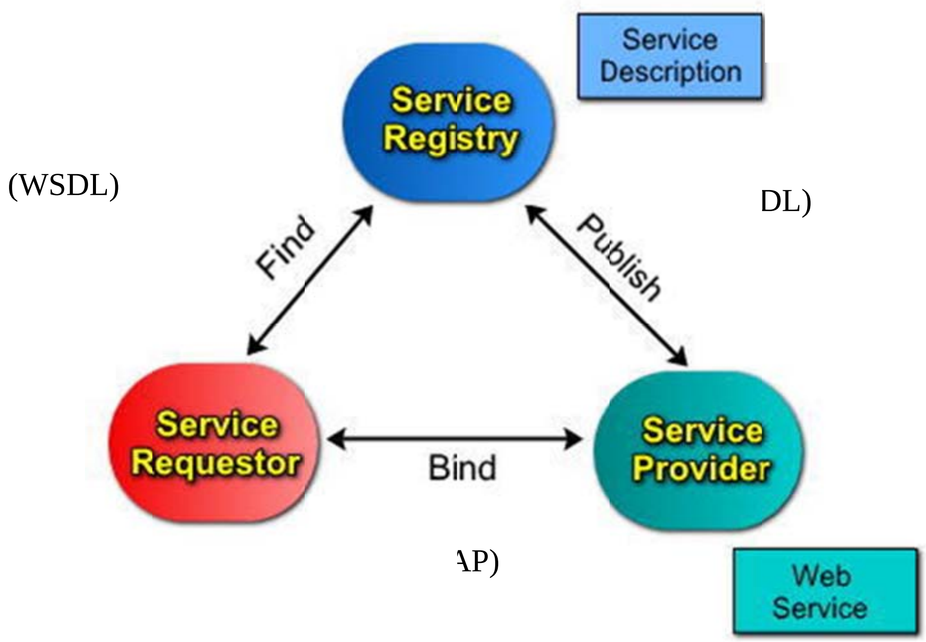

Figure 1: Typical Web Services Data Flow (8)

The key standards with web services (XML, WSDL, and SOAP) are described in greater detail below.

XML (eXtensible Markup Language):

XML is a set of rules for encoding documents electronically. It is defined in the XML 1.0 Specification produced by the W3C, and several other related specifications. It is a simple, very flexible text format derived from Standard Generalized Markup Language (SGML, ISO 8879). Originally designed to meet the challenges of large-scale electronic

publishing, XML now plays an important role in the exchange of a wide variety of data on the web and elsewhere (9).

WSDL (Web Services Description Language):

WSDSL is the most fundamental technology standard associated with the design of services (6 p. 457). A WSDL describes the point of contact for a service provider, also known as the service endpoint or just endpoint. It provides a formal definition of the endpoint interfaces (so that requestors wishing to communicate with the service provider know exactly how to structure request messages) and also establishes the physical location (address) of the service. A WSDL service definition can be separated into two categories.

The Abstract Description establishes the interface characteristics of the web service without any reference to the technology used to host or enable a web service to transmit messages. By separating this information, the integrity of the service description can be preserved regardless of what changes might occur to the underlying technology platform, promoting re-use and graceful technology refresh.

- portType: sorts the messages a service can process into groups of functions known as Operations
    - Operations: represents a specific action performed by the service
        - Messages: input and output communication parameters required to execute an operation

The Concrete Description connects the abstract part of the Web Service to a physical transport protocol, by defining the:

- Binding: a physical transport technology(SOAP being the most common),
- Port: the physical address at which a service can be accessed with a specific protocol
- Service: A grouping of related endpoints (6 pp. 133-136)

SOAP (Simple Object Access Protocol):

SOAP is the universally accepted standard transport protocol for messages processed by Web Services. It is XML-based, flexible, extensible, and can accommodate sophisticated message structures. Every SOAP message is packaged into a container known as an envelope, which is responsible for housing all parts of the message. Each message can contain a header (an area dedicated to hosting meta information). The actual message contents are hosted by the message body, which typically consists of XML formatted data. The contents of a message body are often referred to as the message payload (6 pp. 143-144) .

A primary characteristic of the SOAP communications framework exploited by SOA is an emphasis on creating messages that are as intelligence-heavy and self-sufficient as possible. This results in SOAP messages achieving a level of independence that increases the robustness and extensibility of this messaging framework—qualities that are extremely important when relying on communication within the loosely coupled environment that Web Services require. Message independence is implemented through

the use of header blocks, outfitting a message with the information required for any services with which the message comes in contact to process and rout the message appropriately. This alleviates services from having to store and maintain message-specific logic, reinforcing the SOA characteristics of reuse, interoperability, and composability. The ultimate impact of this approach is that Web Services can be designed with generic processing functionality driven by various types of meta information the service locates in the header blocks of the messages it receives (6 pp. 144-145).

SOA can be distinguished from Web Services, in that SOA principles maintain that the interface presented to the user should not require any knowledge of the specific code implementation or language used (as in some Web Service RPC implementations). Rather, the service should be treated as a black box performing a useful function, with straightforward messages defined via WSDL (rather than calls or other implementation-specific operations disguised as WSDL) being the only things to cross the interface, making loose coupling more likely. Web Services are not a euphemism for SOA. Rather, "service" is the important concept. Web Services are merely a set of protocols by which services can be published, discovered and used in a technology neutral, standard form. (10)

Examine a case study comparing Web Services published by two dotcom companies as alternatives to their normal browser-based access, enabling users to incorporate the functionality offered into their own applications. In one case it was obvious that the Web services were meaningful business services—for example enabling

the Service Consumer to retrieve prices, generate lists, or add an item to the shopping cart.

In contrast, the other organization's services are quite different. It implemented a general purpose Application Programming Interface (API), which simply provides Create, Read, Update, and Delete (CRUD) access to their database through Web Services. This implementation requires that users understand the underlying model and comply with the business rules to ensure that your data integrity is protected. The WSDL tells you nothing about the business or the entities. This is an example of Web services without SOA (10). Although, as seen above, web services can be implemented in a non-SOA fashion, the inverse is not true. Web Services are an inexorable part of SOA

Key Attributes of SOA

SOA builds upon web services by placing a premium on separating "business logic" from the detailed "plumbing" code necessary to implement the logic**.** Fundamental to the service model is the separation between the interface and the implementation. The invoker of a service need only (and *should* only) understand the interface; the implementation can evolve over time, without disturbing the clients of the service. Interestingly, the same interface can be offered by many implementations; several key benefits of service orientation derive from this *abstraction* of the capability from how the capability is delivered (11). A separate and distinct business services layer ensures that the business can respond quickly to new opportunities by making changes only to the applicable *business* services without having to change the underlying

implementation service layers, thereby minimizing the amount of SW maintenance required.

A service's intention is to undertake certain functions to provide value to the business; its specification isn't just the direct service it provides but also the environment in which it undertakes those functions. A service therefore is a discreet domain of control that contains a collection of tasks to achieve related goals. In a good service oriented architecture, these often relate to organizational departments or sub-departments and their functional tasks (12 p. 89). SOA is not just an architecture of services seen from a technology perspective, but the policies, practices, and frameworks by which we ensure the *right* services are provided and consumed (10).

Service Oriented Architecture does maintain several similarities with Object Orientation (OO). Like objects and components, services represent natural building blocks that can be used to organize capabilities in ways that are familiar to a business or organization. Similarly to objects and components, a service is a fundamental building block that:

- Combines information and behavior
- Hides the internal workings from outside intrusion
- Presents a relatively simple interface to the rest of the organism

Further, where objects use abstract data types and data abstraction, services can provide a similar level of adaptability through aspect orientation (providing a means for the consistent handling of cross-cutting concerns, for example the monitoring of business activities, access control to services, and reliability of message delivery). Finally, where

objects and components can be organized in class or service hierarchies with inherited behavior, services can be published and consumed singly or as hierarchies and or collaborations (10).

It is, however, the consumer-oriented view of service that is central to SOA and differentiates it from object orientation. In OO, an object represents what it is, but in SOA, a service represents how its users wish to employ it (12 p. 89). SOA is generally:

- Based on open standards
- Architecturally Composable
- Capable of improving Quality of Service (QoS)

Further it typically supports, fosters or promotes (6 p. 55):

- Vendor diversity
- Discoverability
- Federation
- Extensibility
- Service-oriented business modeling
- Layers of abstraction between business processes and technological implementation
- Enterprise-wide loose coupling

These characteristics of a properly implemented SOA lead to the following organizational benefits:

- Improved integration and intrinsic interoperability
- Inherent reuse

- Streamlined architectures and technical solutions
- Return on legacy IT investments through the employment of SOA adapters
- Out of the box compatibility with "best of breed alternatives," without being locked into one particular platform
- Standardized XML data representation
- Organizational Agility

All this leads to the bottom line that the "cost, effort, [and schedule] impacts incurred to respond and adapt to business or technology-related change is reduced. (6 pp. 60-64)

SOA as Policy with the DoD

As SOAs have gained prominence within private sector and academic circles, the Department of Defense and its subordinate organizations have not sat idly by. Service Oriented Architectures are mentioned explicitly in strategic guidance from the department's most senior officials.

DoD Net-Centric Services Strategy

In March of 2007, the DoD Chief Information Officer (CIO) released a document outlining his intent to build upon the Department's net-centric strategy "to establish a net-centric environment that increasingly leverages shared services and SOAs that are:

- Supported by…a single set of common standards, rules, and shared secure infrastructure

- Populated with [both] mission and business services provided and used by each Mission Area.
- Governed by a cross-Mission Area board chaired by the DoD CIO
- Managed by Global Information Grid (GIG) Network Operations (13 p. i).

The document notes that “as existing threats facing the DoD evolve and as new threats begin to emerge, a new level of responsiveness is required from our forces.” It further points out that the department has historically “focused on system or platform capabilities rather than on mission [area] capabilities,” resulting in “information silos” characterized by “multiple overlapping implementations, limited ability to share information, and a rigid set of capabilities that are unresponsive to the warfighter’s evolving needs (13 p. 1).” In the strategy document, the DoD CIO looks to SOA to play a major role in solving the above problems. SOA is identified as, “a way of describing an environment in terms of shared mission and business functions and the services that enable them (13 p. 2).”

Services are described as “building blocks [that] will facilitate interoperability, provide agility, and improve information sharing” for the warfighter. The CIO goes on to predict that in addition to SOA improving operational effectiveness, weapon system acquirers will also benefit. This is attributed to “services providing a standards-based approach to achieve information sharing,” and because acquisition responsiveness is increased through “cost and resource-effective reuse of capabilities.” “When providers can discover existing capabilities offered as services, they can significantly reduce the time and cost to field a new capability and gain improved interoperability ‘out of the

box.’ By using these ‘building blocks, the DoD can quickly adapt to accommodate the warfighters’ changing mission needs (13 p. 3).” Figures 3 and 4, taken from the document, illustrate the CIO’s perspective on the current information sharing environment (Figure 3), in which capabilities are manifested through stove-piped platforms, contrasted with the paradigm he seeks to implement through SOA (Figure 4), where services are represented as discoverable “building blocks” ready to be assembled into a needed capability.

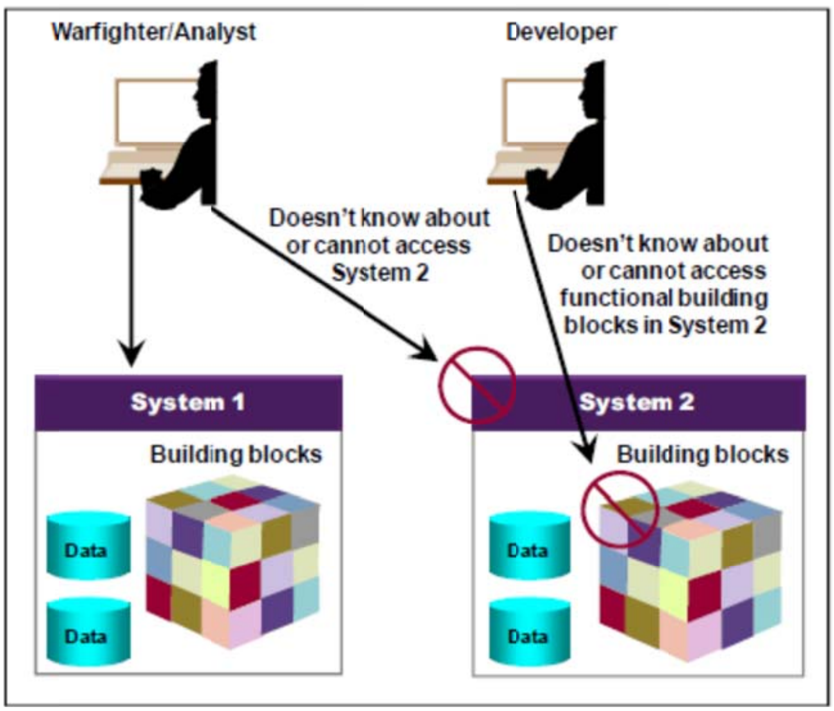

Figure 2: Current Information Sharing Environment (13)

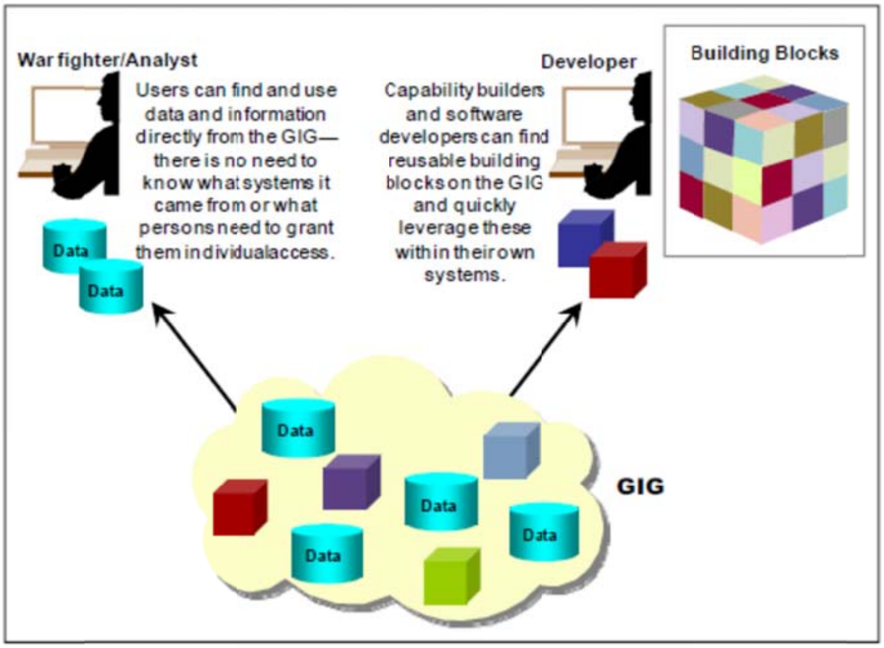

Figure 3 To-be Net-Centric, Service-Oriented Environment (13)

The strategy lays out a series of goals on the path to a service-oriented DoD information enterprise. Examining each of these goals in detail provides further insight into what aspects of SOA the DoD considers most critical:

1. ***Provide Services:*** **Make information and functional capabilities available as appropriately secure services on the network**

The document points out that services can be built or acquired in different ways, but in each case the following actions must be performed (13 p. 6):

- Provide a description of the service and publish it to an enterprise service registry
- Build, appropriately secure, and operate the service
- Manage the performance and lifecycle of the service

In this context, services are explicitly broken down into two categories:

- Mission and Business Services
- Core Enterprise Services

The focus of this thesis shall be on the operational employment and acquisition of SOA-based satellite C2 systems, and therefore the second category, Core Enterprise Services, will be considered outside the scope of this paper. For Mission and Business Services, the document places responsibility squarely on the "Business, Warfighting, DoD Intelligence, and Enterprise Information Environment mission areas to define the mission and business processes along with the specific information and functional capabilities that support them (13 p. 6)." This is a clear indication that the DoD views SOA as far more than an information technology initiative. Rather, it is a means by which warfighters and acquirers can free themselves from the constraints of a particular platform or implementation, and instead present capabilities as generic services for discovery and utilization by anyone. Additionally, the strategy specifies that provided services should be "visible, accessible, and understandable."

2. ***Use Services:*** **Use existing services to satisfy mission needs before creating duplicative capabilities**

This goal is achieved when users look first to consume existing services when filling capability gaps. Regardless of whether one is charged with acquiring capability or employing it, the DoD CIO's intent is for DoD personnel to re-use services that have already been developed.

3. ***<u>Govern the Infrastructure and Services</u>*: Establish the policies and processes for a single set of common standards, rules, and shared secure infrastructure and services throughout the DoD Enterprise to ensure execution enables interoperability**

The strategy recognizes that in order to enjoy the efficiencies gained through SOA, a DoD implementation must be governed from the top down. Particularly during acquisition, standards should be enforced to ensure a common approach and interoperability across systems and mission areas.

AF SOA Playbook

A SOA "playbook" drafted by the office of the United States Air Force (USAF) CIO illustrates how the DoD's focus on SOA has filtered down to the military components for further development and implementation. It explicitly maps SOA-related information technology "tactics" to AF Mission Objectives.

The document's executive summary identifies an ambitious set of specific goals and objectives for a successful SOA implementation across the Air Force enterprise. The AF CIO seeks to improve the way information is delivered to users, promote re-use and prevent the duplication of exiting capabilities, thereby slashing deployment and sustainment costs. In essence, the playbook codifies the Air Force's aspiration to reap many of the benefits promised by SOA that are documented in above. In describing the AF SOA vision, the document states (14):

> "A well architected SOA provides top to bottom management visibility of existing services, so one doesn't go on a "scavenger hunt" for any given application. A SOA provides for a more rapid method of distributing applications and increased agility. By leveraging and reuse of existing enterprise software, infrastructure, and networking/bandwidth, the costs of custom integration and interoperability are lowered. Manual tasks are reduced or eliminated (14)."

The playbook recognizes that the process of implementing SOA across the Air Force is likely to be an arduous one. It notes a series of key challenges ahead (14 pp. 3-4):

- Acquisition Force Transformation
    - Shifting technical development paradigm from systems to SOA
    - Educating SPOs/PMOs on the process
    - Acquiring SOA skills from small, agile contractors
- Agile Service Delivery
    - Re-engineering AF Acquisition Processes
    - Dynamic Testing – Re-engineering AF Testing Processes
- Initial Investment required:
    - Subject Matter Experts for upfront vocabulary work
    - Support to functional leads across the service to expose their data
    - Support Acquisition Community for centralized configuration management

- Transitioning to a centrally managed, end-to-end, capability based, federated infrastructure

SOA in Satellite C2

The SOA movement has not gone unnoticed by ground system experts in the satellite command and control community. The bulk of the interest to this point has focused on using SOAs to efficiently acquire and field satellite C2 systems.

The National Aeronautics and Space Administration (NASA), facing uncertain budgets in out years and a severely cost-constrained environment in general has been particularly keen to find a more cost-effective model for controlling its unmanned space systems. According to NASA, the Goddard Space Flight Center (GSFC) Mission Services Evolution Center (GMSEC) reference architecture provides a scalable, extensible, ground and flight systems approach for future missions. The architecture enables quick and easy integration of functional components that are selected to meet the unique needs of a particular mission. The architecture enables the addition, deleted, and exchange of components to meet the changing requirements of missions as they progress through their lifecycles and provides a rapid, flexible, and cost-effective means to meet a wide variety of evolving mission concepts and challenges (15).

GMSEC enables this system-level development approach by maintaining the reference architecture, defining standard messages, and supplying interface software. GSFC Information Systems Division and Mission Engineering and Systems Analysis Division provide software development of functional components. Missions then select

those components that best fit their operational needs. By utilizing this approach, organizations can prepare a satellite C2 system tailored to their requirements at a lower cost that is "out of the box" interoperable with other GSFC GMSEC based systems. Additionally, as technology advances or operational requirements change, new components can be added or existing components can be swapped in and out of the system with low risk and minimal integration effort (15).

Although NASA uses the words "components" (vice services) in its description of GMSEC, the architecture shares many SOA principles. It features plug-and-play components, standard messaging, and a software information bus (also known in SOA parlance as an "enterprise service bus") (15). Like SOA, it emphasizes the standardization of both components (i.e. services) and interfaces. In an American Institute of Aeronautics and Astronautics (AIAA) submitted paper at the 7th Responsive Space Conference, experts studying methodologies for improving ground segment acquisitions called GMSEC a "good example" of a SOA-modeled ground implementation. The paper went on to assert that GMSEC's message bus middleware provided a serviced-based interface between Satellite Operation Centers (SOCs) that was automated and SOC agnostic (16). GMSEC has supported eight orbiting satellites and is being applied to several of NASA's future missions. NASA's ST5 mission was its first to be fully GMSEC compliant. It appears to be a viable standard communications infrastructure for compatible command and control interfaces, messaging, and data formats (17). Figure 5 illustrates GMSEC's "plug and play" design intent. Figure 6 then

depicts GMSEC's ability to accommodate a variety of implementations to meet mission-specific functional requirements.

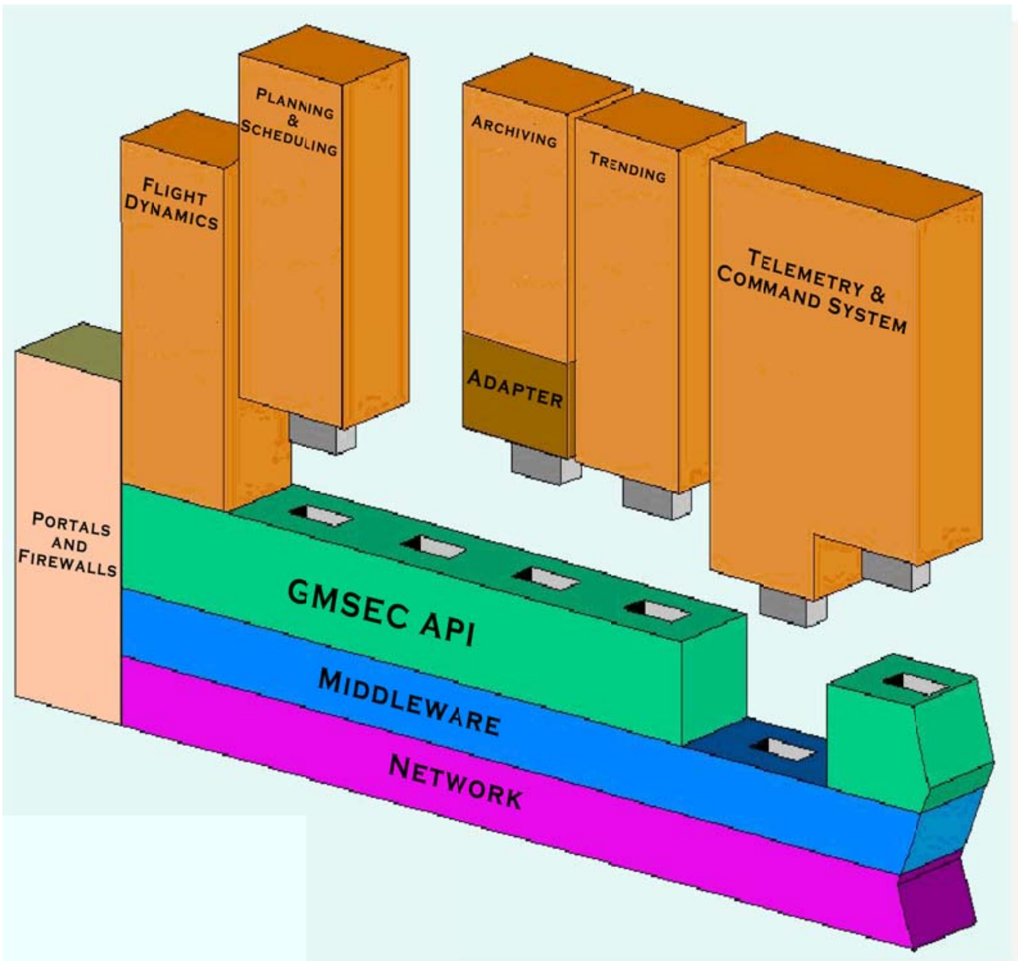

Figure 4: GMSEC Architecture (18)

Across the country at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, researchers explored the benefits of implementing SOA solutions for organizing and making accessible the large amounts of scientific data gleaned from its "A-Train" constellation of earth-observing and climate trending satellites. To simplify access to large and complex satellite data sets for climate analysis and model verification,

a service-oriented architecture-based tool was developed to help study long-term and global scale-trends in climate, water and energy cycle, and weather variability (19).

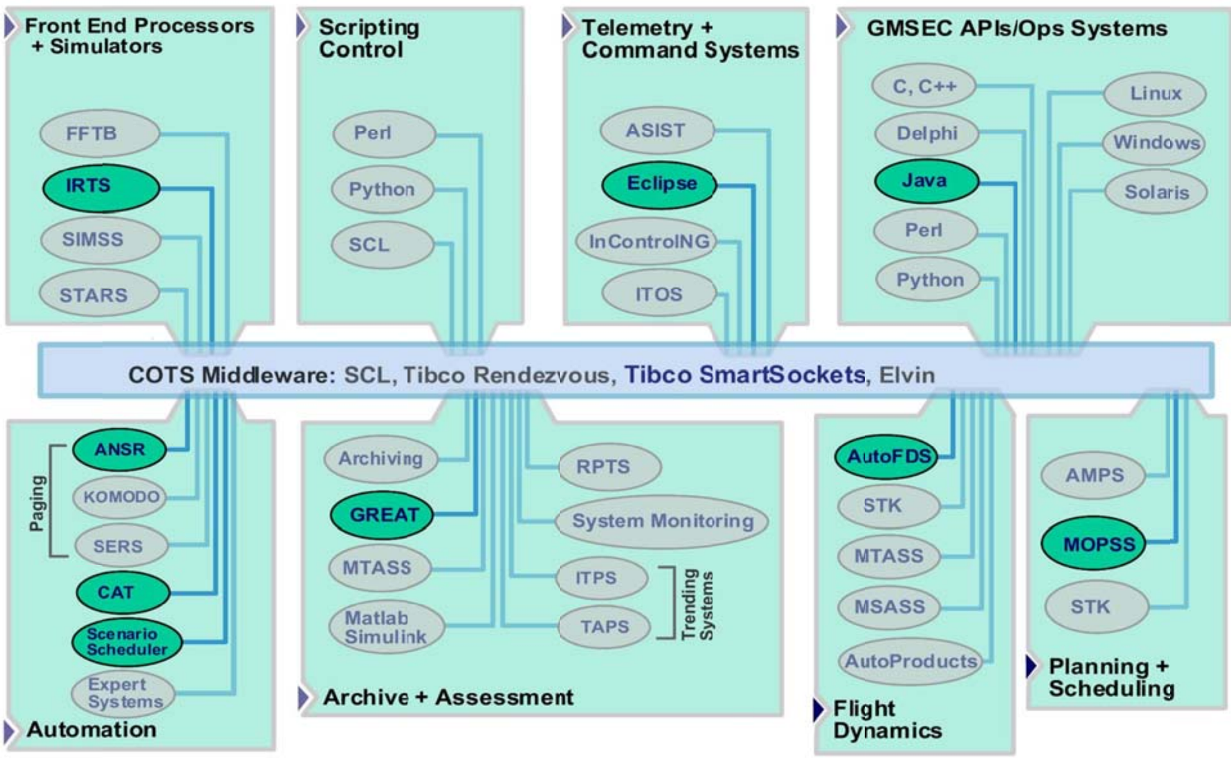

Figure 5: Open (non-proprietary) nature of GMSEC

Historically, the volume and inhomogeneity of the data had been difficult or time consuming to search and acquire, resulting in analyses that tended to be small-scale or short-term. Recognizing that web-based analysis environments can be rigid and limiting to an external user, the JPL researchers identified the need for well-designed distributed services so that users can perform analysis in their own familiar computing environments (19).

To meet this need, the researchers created “voluminous, merged” data sets and provided server-side capabilities developed to off-load processing and reduce the amount of data to be transferred to the client. Finally, multiple client-side processing APIs were developed to enable scientists to perform analysis of the data from within their own familiar computing environment (Java, Python, Matlab, IDL, C/C++, and Fortran90). Merging, clustering, subsetting, averaging, and summarization web services were created to enhance the accessibility and analysis of A-Train Data. The developers believed a major benefit of utilizing Web Services was the true interoperable nature of their implementations. One set of server-side Web Services paired with multiple sets of client-side services enabled the use (and re-use) from multiple heterogeneous environments and varying client implementations. In the end, the researchers concluded that by developing a service-oriented architecture for discovering, accessing, and manipulating merged A-Train data sets, they “strengthened the interconnectedness and reusability of these services across a broader range of Earth science investigations (19).” It is not hard to imagine similar benefits in a defense or national security space context, perhaps to improve access, analysis, and exploitation of overhead imagery analysis.

Also at the Jet Propulsion Laboratory but as part of a different activity, the Advanced Multi-Mission Operations System (AMMOS) is looking to procure and install the Deep Space Information Services Architecture (DISA), an enterprise class registry and repository for all future Deep Space Network (DSN) and AMMOS SOA implementations. The organization is also developing a Mission data Processing and Control Subsystem (MPCS), which uses JAVA and XML for messages and a SOA

message bus for communications management. Specifications and standards for these efforts are homegrown under the direction of the DISA Chief Software Architect (20).

NASA is not the only federal agency looking to realize the benefits of Service Oriented Architectures for space-related applications. As described above, the Department of Defense initiated policies directing its subordinate components to conform to its Net-centric Services Strategy. US Air Force Space Command (AFSPC), the echelon within the Air Force tasked with the acquisition and operation of space-related defense systems, has begun to examine ways to more efficiently acquire and deploy new satellite C2 platforms. Accordingly, it is investigating SOA as a potential critical enabler of those objectives.

In a written directive to his staff and subordinate commands in late 2008, AFSPC Commander General Robert Kehler highlighted the importance of establishing a common satellite command and control paradigm and moving “expeditiously toward open/service-oriented…systems for AFSPC satellite programs:

> “The focus [should be on] developing more efficient SATOPS architectures and identifying requirement commonalities, enabling consolidation of functions and capabilities, reducing duplication and improving interoperability at all levels…Any future AFSPC SATOPS enterprise architectures must not only address an open architecture, but also legacy system requirements and infrastructures ensuring we provide improved space situational awareness, defensive space control, and operational responsive space capabilities, enabling AFSPC to meet

National Security Space objectives and Joint warfighter operational needs" (21)

While giving an address convening the 2009 Ground System Architectures Workshop (GSAW) conference in Los Angeles, USAF Lieutenant General Tom Sheridan, Commander of the Space and Missile Systems Center (SMC) and the officer charged with overseeing Air Force space acquisition efforts on behalf of AFSPC, echoed Gen Kehler's vision of ground systems being able to interoperate effectively and deliver capability to the warfighter at the "speed of need." In particular, he noted the imperative to develop an open, efficient, service-oriented architecture with shared commonalities across platforms. The goal, he said, should be consolidation of functions and capabilities via non-proprietary implementations, eliminating redundancies and duplication of work. Lt Gen Sheridan declared that any future AFSPC satellite operation enterprise architecture must address not only this need for openness and interoperability going forward, but should also be backwards compatible with existing legacy systems (22).

Clearly, in the eyes of Air Force senior space leadership, the days of closed, stove-piped, and redundant systems are over for space system ground architectures. The DoD Operationally Responsive Space (ORS) office, an organization reporting administratively to the DoD Executive Agent for Space and chartered expressly to improve the responsiveness of the department in providing needed space effects to the warfighter, is also aggressively pursuing mechanisms for rapidly constituting ground segments for DoD space capabilities. ORS identifies SOA as a preferred means to meet its goal of developing what it terms a "responsive ground system enterprise." The

office is supporting activities to establish a compatible architectural framework for satellite operations (17), and has invested in initiatives across the three services (Air Force, Army, and Navy) as well as other agencies like NASA and the National Reconnaissance Office (NRO).

Key capabilities for the 2015 timeframe include autonomous operations for multiple constellations of small satellites; synchronization of ORS assets with other available capabilities; payload tasking and request tracking through a simple user interface; standard vehicle maintenance; payload mission planning; standard command and control of the spacecraft through ground-based and space-based relay; collection of telemetry and mission data through ground-based and space-based relay; processing and dissemination of telemetry and mission data to joint force commanders or provision of direct downlink to a warfighter in theater; and rapid transition of spacecraft demonstrations and prototypes to operational use (17).

In addition, a number of ancillary needs are being considered. For example, according to ORS the ground system enterprise should incorporate a modular open-system architecture to promote innovation, standardization, and nonproprietary development. It should connect to exercise and war-game engines and integrate with the global information grid. It should allow autonomous mission planning, data processing, and data distribution and support system-level testing. It should incorporate a responsive information assurance program, a responsive configuration management process, and a responsive frequency management system. It must support, at multiple levels of security, ORS missions involving electro-optical/infrared systems, non-imaging infrared systems,

signal intelligence, synthetic aperture radar, space and terrestrial situational awareness, mobile communications, and blue-force tracking. Lastly, it must assign sufficient network priority to ORS missions to expedite the upload of mission tasking and the download of mission data (17).

The Multi-Mission Satellite Operations Center (MMSOC) ground system architecture has been designated as the primary satellite command and control capability for Air Force missions within the ORS Office. The Block I architecture will be used to support the STPSat-2 mission in 2010. It is also installed at one of the satellite operations centers (SOC-11) at Schriever Air Force Base in Colorado Springs to support ORS's first operational satellite: ORS-1. The Block II study phase was initiated in early 2009, in keeping with the program's incremental approach for yearly block upgrades (17).

The MMSOC Ground System Architecture (GSA) program's end goals, design methodology, and acquisition strategy have much in common with Service Oriented principles. The Responsive Satellite Command and Control Division of the SMC Space Development and Test Wing, in conjunction with its contractor team, developed a strategy for implementing a published future architecture. The strategy employs an evolutionary model guided by an open-systems management plan with interfaces controlled by an architecture services catalog and external interface control document. The open-systems management plan was based on fundamental open-system principles: establish business and technical enabling environments; employ modular concepts; employ business and technical patterns; designate key interfaces; and use open standards for key interface certification and conformance. These principles, combined with the

identification of standards (particularly for data and interface control) and the established catalog of services, will allow the program to work with a range of potential missions, reducing unique mission support requirements (17).

Service Views in DoD Architecture Framework (DODAF) v2.0

According to the latest release (version 2.0) of the Department of Defense Architecture Framework, an architecture development methodology specifies how to derive relevant information about an enterprise's processes and business or operational requirements, and how to organize and model that information (23 p. 48). The document specifies in detail a six step process for developing architectures. Further, it explicitly states, "the methodology described in this section is applicable to development of SOA-based Architectures (23 p. 49)." Indeed, an entire service-related viewpoint (set of views) is detailed in Volume 2 (24 pp. 190-206).

The following DoDAF v2.0 views will be provided in this thesis:

- Operational Viewpoint
  - OV-5: Operational Activity Diagram
- Services Viewpoint:
  - SVCV-4: Services Functionality Description
  - SCVC-5 : Operational Activity to Services Traceability Matrix

III. Methodology

This chapter will focus on the methodology to be used in answering the research questions. What services are suitable for a space C2 SOA implementation? How are they related? How can they be assessed or evaluated for near-term implementation?

Answering these questions will require aspects of both service oriented design as well as service oriented analysis. The results will be illustrated utilizing many of the DoDAF service views discussed in section 2.4. This thesis will use a similar approach to that prescribed within DoDAF in the development of notional services for use satellite command and control. It will follow the six step architectural development process (23):

1. Determine the intended use of the architecture
2. Determine the scope of the architecture
3. Determine the data required to support architecture development
4. Collect, organize, correlate, and store architecture data
5. Conduct analyses in support of architecture objectives
6. Present results in accordance with decision maker needs

With respect to defining services, the methodology specified in the DoDAF, volume 2, will be used as a guide. The following steps can be taken to capture Services information to support the intended purpose of the architecture:

- Identify and capture the capabilities supported or provided by the services

- Identify and capture the operations, business functions and activities supported or automated by the service
- Identify and capture the Organization responsible for providing the services
- Using the Service Description, capture the information to be consumed by the service and the information that is being produced by the service (24 p. 99)

As this thesis aims primarily to specify these services from a functional rather than technical standpoint, subsequent steps of this process (associated with physical/logical interfaces, performance requirements, etc.) will be left to future researchers.

While defining a set of services and their interactions (as described above) is a worthwhile and necessary step, it does not fully answer the research question, particularly in the area of suitability. In order for a service to be deemed "suitable," it must engender the characteristics identified in Chapter II (SOA Key Attributes). If the service cannot embody these attributes in order to capture the benefits promised by SOA, then the question must be asked, "why go through the trouble of converting the functionality to a service to begin with?" In analyzing this research question, this thesis will focus on addressing the degree to which satellite C2 functionality can be converted and meet the accepted description of a bona fide SOA service.

Selected SOA characteristics will form a set of criteria allowing for a disciplined evaluation of how each identified service stacks up against the inherent qualities of a "suitable" SOA. The template for this comparison can be seen in Table 1, and the criteria are described further below. In cases where a particular approach is required to achieve a

SOA benefit it will be annotated and fully described, therefore identifying the highly impactful design/development considerations for future satellite C2 SOA efforts.

Table 1: Candidate Service Evaluation Matrix

Evaluation Matrix for Candidate Satellite C2 Services		Level of Support to the Mission (consistency with business/ops processes)?	Architecturally Composable (decompose into smaller or aggregate into larger services)?	Level of Commonality Across Missions	Level of Propriety (locked into vendor-specific solutions)	Criticality of Performance (QoS) Requirements
Criterion Weight:		10.0%	10.0%	30.0%	20.0%	30.0%
Candidate Services	a					
	b					
	c					
	..					
	x					

The criteria in Table 1 are assembled from the SOA characteristics in Chapter 2 (many referenced from (6)) and are described in detail below:

- **Level of Support to the Mission (consistency with business/ops processes):**

In accordance with the "business" modeling aspect of SOA, this criterion analyzes the consistency of the service functionality with actual operational processes within the DoD space enterprise.

- **Architecturally Composable (decompose into smaller or aggregate into larger services)?**

One of the key characteristic of SOA, as mentioned previously, is that services can build upon each other to create aggregate services. Likewise, they can be decomposed to isolate services that best apply to the objective of the architecture. This quality adds flexibility while maintaining standardization and reusability.

- **Level of Commonality Across Missions**

If Service Oriented Architecture were to benefit the Satellite C2 enterprise within the DoD, then clearly much of the value would come from the potential for re-use across missions, reducing the need for redundant development efforts. Any Service design effort, therefore, should look to maximize the degree of commonality.

- **Level of Propriety (locked into vendor-specific solutions)**

Service Oriented Architecture is predicated on the idea that it can bring long term flexibility to an enterprise. The construction of services based on actual business/operational processes and the utilization of web service standards foster an ability to evolve (and tech refresh) an architecture over time. They also promote inherent interoperability across missions. Proprietary implementations undermine this construct and the associated potential benefits.

- **Criticality of Performance (QoS) Requirements**

Stringent Quality of Service (QoS) requirements complicate Service Oriented implementations. The flexibility gained through generic messaging schemes like XML and SOAP, implemented through WSDL interface definitions and aggregated into loosely coupled services, must be tempered by the potential unintended consequences of so many moving parts. SOA vendors have recognized this issue and are increasingly offering

diagnostic tools to isolate the services causing performance issues (latency, availability, reliability, etc.) and quickly resolve the problem. Nevertheless, performance requirements should be assessed on a service-by-service basis as one component in determining overall "suitability" for that functionality to be presented through a SOA.

The suitability of each set of candidate services will be scored using a Value Focused Thinking (VFT) model with the following measures:

- *High Suitability (HS) – Score: 3.0*

A highly suitable score indicates a functionality that, with respect to the indicated criterion, can be presented as a service without prohibitive challenges and which is likely to yield the benefits desired from a SOA (e.g. support to the mission, composability, commonality, openness).

- *Moderate Suitability (MS) – Score: 2.0*

A moderately suitable candidate service may have certain characteristics making its associated functions challenging to implement in a SOA.

- *Low Suitability (LS) – Score: 1.0*

A candidate service scored with a low degree of suitability represents functionality that (with respect to the selected criterion) is not ready to be transitioned to a SOA in the short term. Presenting this functionality in the form of a service would be inconsistent with the current state of technology, policy, or accepted practice, and would therefore be unrealistic without the presence of some paradigm-changing enabler.

In addition to the scoring scheme described above, each criterion is weighted according to its relative importance. Of the possible benefits the Department of Defense

stands to yield from implementing a satellite C2 SOA, the ability to re-use services across multiple platforms and mission areas has the largest potential to reduce cost and improve schedules, and is therefore highly weighted. Similarly, the degree of dependency the functionality has on QoS requirements will make implementing a service for that function significantly more challenging; therefore, that criterion is also weighted relatively high. In summary, for each criterion, the greater the impact for the DoD on the overall SOA value proposition, the greater the weighting factor. The weighting factors are also described in Table 1.

Lastly, the results of this service-by-service evaluation will be summarized using a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis. The goal here will be to assess what functionalities are best suited (strengths) to an immediate SOA implementation and which face significant challenges (weaknesses). Additionally it will identify any enablers (opportunities) that can be put in place to better facilitate a transition to SOA, and what external or institutional impediments (threats) exist against SOA principles.

Both the VFT and SWOT analyses will be performed by a subject matter expert with experience in the acquisition (design, development, fielding, and test) of satellite ground systems as well as having a background in the operational command and control of a wide range of space assets. This ensures both the acquisition and operational perspectives are accounted for in assessing value and identifying strengths, weaknesses, opportunities, and threats.

IV. Analysis and Results

This chapter will utilize the methodology presented in Chapter III to analyze what satellite C2 functionality can be suitably presented as services in a SOA, and what programmatic and/or operational benefits might result. Figure 7 depicts the OV-5 Operational Activity view for a generic DoD C2 architecture. The high-level activities are broken down as follows:

- Generate Tasking
- Plan and Schedule Satellite Operations
- Execute Real-time Satellite C2
- Execute Tasking
- Collect, Process, and Analyze Data
- Create and Share Info Products
- Track and Report Status of Mission(s) and Operational Resources

These activities are generic; they are not particular to a specific mission area, platform, or implementation. Following the Structured Analysis IDEF0 format, inputs are depicted entering a box from the left and outputs leaving from the right. Constraints and mechanisms are applied to a given activity from the top and bottom, respectively.

"The intent of IDEF0 is to provide a means for completely and consistently modeling the functions (activities, actions, processes, operations) required by a system or enterprise, and the functional relationships and data (information or objects) that support

the integration of those functions (25)." While more recent modeling languages exist (Unified Modeling Language, System Modeling Language, etc.), given its emphasis on functionality, IDEF0 was appropriate for this analysis.

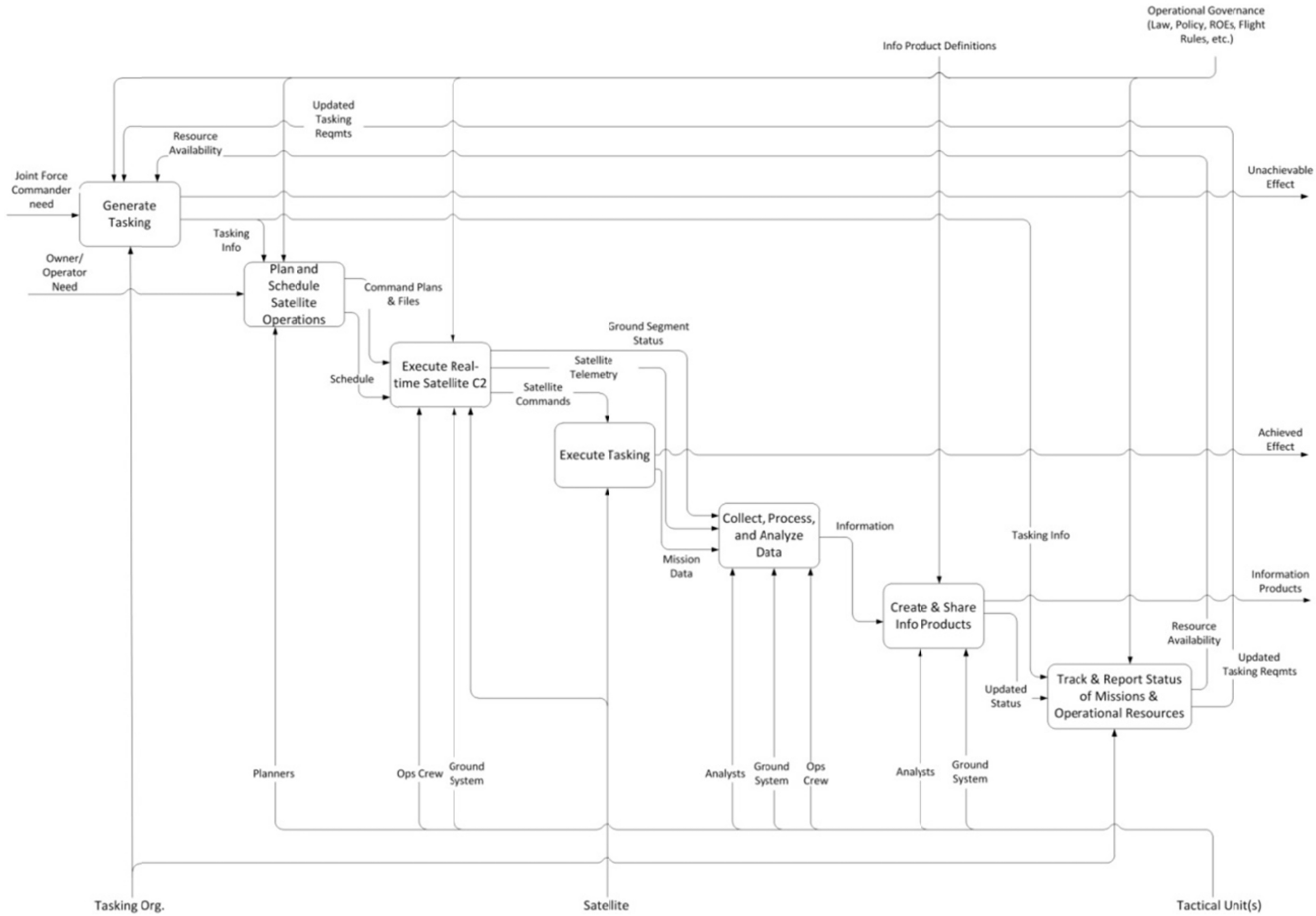

Figure 6: Satellite Operations OV-5 – Operational Activity Viewpoint

Service Descriptions

Following the methodology outlined in Chapter III, a set of candidate services for satellite command and control is presented below via a SvcV-4 viewpoint (Services Functionality Description). Presented as a Taxonomic Service Functional Hierarchy, Figure8 shows a decomposition of service functions depicted in a tree structure.

The set of services outlined is composable, meaning it consists of aggregate services comprised of lower-level component services. As mentioned previously, this is an important characteristic of SOA. Also noteworthy is set of shared services seen on the right side of Figure 8. These services cut across multiple areas to provide reusable functionality to the entire architecture that does not need to be duplicated within each function. The overarching candidate services are decomposed two levels deeper. This is not deep enough to accurately convey implementation (which is not the intent of this thesis), but it does show how satellite C2 functionality can be organized into a notional SOA. It is important to note the service functions identified in the SvcV-4 are not newly conceived. Rather, they aim to consolidate and standardize the generic functionality that must be performed by any satellite command and control architecture. When organized into a SOA, the intent is that these functions become composable, discoverable, and interoperable for any given platform or mission, fostering reuse. Further, the extensible nature of SOA (particularly its well understood interface definitions through the use of WSDL), allows for the development of mission-unique functionality not provided by existing services.

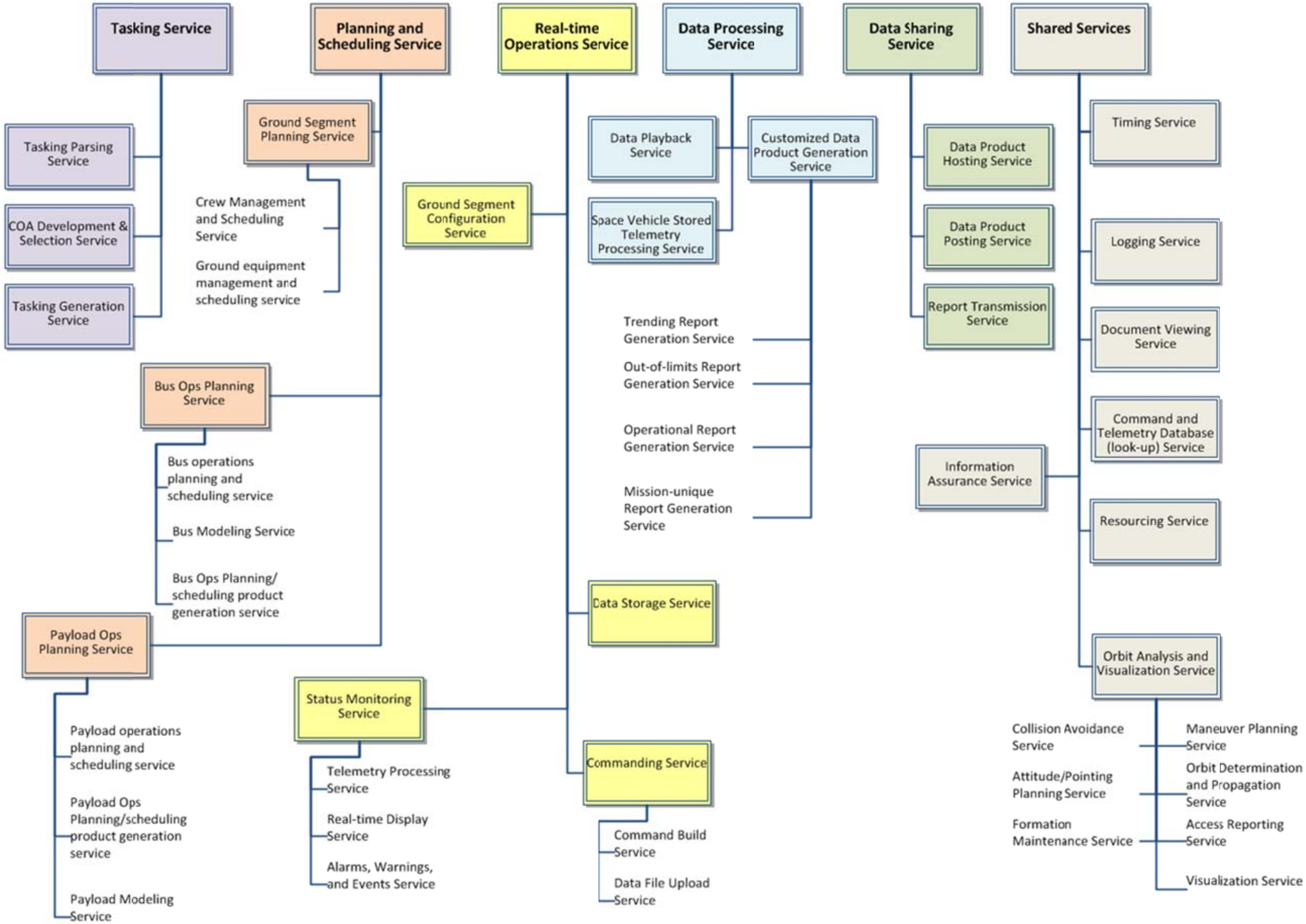

Figure 7: SvcV-4 Services Functionality Description (Taxonomic Service Functional Hierarchy)

The SvcV-5 shows the relationship between the operational activities depicted in the OV-5 and the services identified in the SvcV-4. The relationship between operational activities and service functions can be expected to be many-to-many (i.e., one activity may be supported by multiple service functions, and one service function may support multiple activities).

Table 2: SvcV-5 – Operational Activity to Services Traceability Matrix

SvcV-5: Operational Activity to Services Traceability Matrix		Generate Tasking	Plan and Schedule Satellite Operations	Execute Real-time Satellite C2	Execute Tasking	Collect, Process, and Analyze Data	Create and Share Info Products	Track and Report Status of Mission(s) and Operational Resources
Tasking Service	Tasking Parsing Service	X			*No Traceability to Ground Services (function performed solely by satellite)*			
	COA Development & Selection Service	X						
	Tasking Generation Service	X	X					
Planning and Scheduling Service	Bus Ops Planning Service		X	X				
	Payload Ops Planning Service		X	X				
	Ground Segment Planning Service		X	X				
Real-time Operations Service	Ground Segment Configuration Service			X		X		
	Commanding Service			X				
	Status Monitoring Service			X		X		
	Data Storage Service			X		X		
Data Processing Service	Space Vehicle Stored Telemetry Processing Service					X		
	Customized Data Product Generation Service						X	X
	Data Playback Service					X		
Data Sharing Service	Data Product Hosting Service						X	
	Data Product Posting Service						X	X
	Report Transmission Service						x	x
Shared Services	Timing Service			X		X	X	
	Resourcing Service	X	X					X
	Orbit Analysis and Visualization Service	X	X	X		X	X	X
	Command and Telemetry Database (look-up) Service		X	X		X	X	
	Document Viewing Services	X	X	X		X	X	X
	Information Assurance Service	X	X	X		X	X	X
	Logging Service	X	X	X		X	X	X

A description of each service identified in the SvcV-4 is provided below. These services, while not described in technical detail, do convey how a satellite C2 SOA might be functionally organized. Additionally, for each set of services (apportioned by the six categories identified above) an analysis will be conducted identifying the associated strengths, weaknesses, and required enablers.

1. Tasking Service

This service identifies space tasking requirements and the associated constraints, prioritizes those requirements, and develops Courses of Action (COAs) in accordance with those priorities and available resources. Finally, the service creates and sends actual tasking orders to the tactical unit for execution. It is comprised of three component services as described below:

1.1. Tasking parsing service

The tasking parsing service receives tasking requests from supported organizations, or internally generates requests for standing taskings, identifies the desired effect along with any constraints associated with the request. It also prioritizes all the requests made to the service across the enterprise based on a predetermined schema.

1.2. COA development & selection service

This service evaluates any constraints associated with a request to check for validity and feasibility. It then checks resource availability (pulling from the resourcing service to be discussed later), and develops a set of operational-level COAs that meet the

tasking constraints. Next, it assesses these COAs on the basis of risk, consumables required, and opportunity cost. Based on this logic, the service will select a preferred COA.

1.3. Tasking generation service

The tasking generation service creates the actual tasking order based on the selected COA, transmits the order to the tactical unit(s), and updates the resourcing service (which is enterprise-wide) to update the future status of the assets needed to complete the tasking.

2. Planning and Scheduling Service

The planning and scheduling service will plan and schedule satellite operations, either in support of mission-related (payload) taskings or spacecraft maintenance/ housekeeping activities. It is comprised of many secondary and tertiary services, which are described in further detail. Because the bus and payload for each DoD space mission can differ widely, actual service implementations for this functional area can and should vary accordingly. Care should be taken, however, to not duplicate functionality and to limit development efforts to truly mission-unique requirements. Additionally, the way the planning and scheduling services interface with enterprise level services should remain standardized.

2.1. Bus Ops Planning Service

The Bus Operations Planning Service focuses on generating command plans for housekeeping or maintenance-related activities. It is comprised of three component services which are further described.

2.1.1. Bus modeling service

This service models the bus for use by other planning services, defining pointing capabilities and limitations, thruster configurations, power and memory management schemes, etc. It is by definition spacecraft unique, but will follow standardized conventions for units, data types, etc.

2.1.2. Bus operations planning and scheduling service

This service plans and schedules the bus-related operations per the spacecraft modeling constraints.   Common activities to plan can include:

- Bus on-orbit recurring maintenance (such as battery reconditioning, reaction wheel momentum dumping, eclipse actions, etc.)
- Memory management (ensuring state-of-health data is stored and downlinked without exceeding limits)
- Bus communications (transmitter on/off times)
- Miscellaneous housekeeping activities

2.1.3. Bus Ops planning/scheduling product generation service

This service generates products based on the planning activities completed above. These products can include spacecraft contact command plans, schedules identifying when the ground will have opportunities to communicate with the spacecraft, daily mission plans identifying what activities will be completed at what time, and others as required by the mission. It can also create files that will be uploaded to the spacecraft for execution onboard. This service will standardize these products across mission areas where possible, and provide the ability for unique extensions or additions where required.

2.2. Payload Ops Planning Service

This service is focused on planning how to fulfill the tasking handed down from higher headquarters. The tasking can be categorized in one of several different mission areas, and the planning for each area should be standardized across the enterprise to the extent possible:

- MILSATCOM
- ISR
- Positioning/Navigation
- Missile warning
- Space Control
- Other (R&D, tech demo, etc.)

2.2.1. Payload modeling service

In a similar fashion to the bus modeling service, this service models the specific constraints and capabilities of the satellite payload(s).

2.2.2. Payload operations planning and scheduling service

Using the information provided from the payload modeling service, this service plans and schedules payload operations, which will be used to complete the tasking.

2.2.3. Payload operations planning/scheduling product generation service

This service creates files, schedules and other planning products associated with the spacecraft payload.

2.3. Ground Segment Planning service

Like the bus and the payload, the equipment and personnel making up the mission ground segment are assets that must be planned for and scheduled. The ground segment planning service provides this functionality.

2.3.1. Crew management and scheduling service

This service manages personnel requirements and metrics associated with a given mission. In an integrated architecture, human operators, along with their associated functions and constraints should be accounted for just as one would account for hardware

and software. This service provides that functionality and ensures the information can be utilized by the rest of the architecture.

2.3.2. Ground equipment management and scheduling service

This service provides planning and scheduling functionality in regard to the chain of ground equipment needed to communicate with the on-orbit asset, which can include equipment located locally at the Satellite Operations Center (SOC), the communications paths carrying downlink and uplink information to and from the remote antenna, and the set of equipment at the remote antenna itself. The service also plans and schedules ground maintenance, regardless of whether the activity is routine/periodic or unscheduled in response to a technical problem.

3. Real-time Operations Service

The real-time operations service contains the set of component services necessary to conduct satellite command and control in real-time (meaning in active contact with a space asset). To conduct real-time operations, it is necessary to configure ground equipment, conduct satellite commanding, receive and process ground and space segment telemetry, and store data for further analysis. The services providing this functionality are discussed in greater detail below.

3.1. Ground Segment Configuration Service

The ground segment configuration service controls ground segment equipment. It configures and de-configures local HW/SW, communication links, and antenna HW/SW.

3.2. Commanding Service

This service generates the uplink information for transmission to the spacecraft. It is comprised of two component services which send spacecraft commands and data files respectively.

3.2.1. Command build service

The command build service selects the proper command from the spacecraft command and telemetry database, parameterizes and formats it, transmits it to the spacecraft, and keeps track of all commands sent.

3.2.2. Data file upload service

The data file upload service formats and transmits files (tables, flight software updates, communications schedules, etc.) to be uploaded for processing onboard the satellite.

3.3. Status Monitoring Service

This service monitors the ground and space segments and provides processed information in real-time. It does this processing by processing telemetry, displaying that information, and providing notifications of alarms, warnings, or other events of interest.

3.3.1. Telemetry processing service

The telemetry processing service processes raw telemetry received from the spacecraft (demodulates, de-multiplexes, frame synchronizes, de-commutates, etc.).

Once the raw telemetry is processed it is both stored in raw form (utilizing the data storage service below) and converted from binary to meaningful engineering units.

3.3.2. Real-time display service

This service displays the engineering-unit converted data to the operator. Telemetry is organized and formatted in a user-configurable fashion in order to maximize operational suitability and overall functionality.

3.3.3. Alarms, warning and events service

This service monitors status of the space, link, and ground segments and indicates alarms, warnings, and other events of interest. It interacts primarily with the real-time display service but also others as needed (logging service, data product generation service, etc.).

3.4. Data storage service

In satellite command and control it is almost always necessary to record data downlinked from the satellite, primarily for use in later analysis, trending, or contingency analysis. This service provides that functionality.

4. Data Processing Service

This service turns data into useful information. It processes telemetry that is not needed real-time, and generates user-customized reports for the operator, engineers, or higher headquarters. This service also allows stored data to be played back through the real-time operations service, which is often useful in responding to operational contingencies.

4.1. Space Vehicle Stored Telemetry Processing Service

Not all telemetry is processed in real-time. Large volume information like Stored State of Health data, for example, is typically processed separately from information that needs to be stored immediately. Other information like command histories, system logging data etc. must be collected and sorted according to groupings that are useful to the consumer.

4.2. Customized data product generation service

Once data has been stored and processed into useful information, that information can be used to populate reports. To maximize their effectiveness, these reports should be tailored to the consumer's requirements. The below services provide common types of reports used by satellite controllers and engineers:

4.2.1. Trending report generation service

4.2.2. Out-of-limits report generation service

4.2.3. Operational report generation service (OPSCAP, OPREP, SITREP, etc.)

4.2.4. Mission-unique report generation service (extensible to meet an individual mission's unique information product requirements)

4.3. Data playback service

At times, it can be useful to playback data in order to analyze something (a telemetry value of interest at a certain time, for example) that may have been missed in real-time. This service provides that functionality.

5. Data Sharing Service

Data products lose their value if they do not reach a consumer that can exploit the information contained within. This service provides combination of push/pull functionality to ensure that data is not only available to a wide range of authorized users, but that time critical products are transmitted directly to users that need them.

5.1. Data product hosting service

This functionality is implemented as a standard web-service portal, providing secure, discoverable data products available to authorized users. It interacts with the data product generation service to provided tailored products or reports to users.

5.2. Data product posting service

This service allows satellite operators and analysts to make specific information products available to the data product hosting service.

5.3. Report Transmission Service

In certain situations, it is not sufficient to make data available to users. For example, higher headquarters may have a time critical requirement to receive operational or ops capability reporting within a specified time period following an event. Likewise, users in the field may need to have certain data pushed to them on the fly, rather than take the time to log into the data product hosting service and pull it themselves. This service provides the ability for satellite operators and data analysts to transmit information products directly to the user(s).

6. Shared Services

One of the key benefits of Service Oriented Architecture is the ability to prevent duplication of development effort through the re-use of common services. Because so much of satellite command and control relies on a common underlying IT infrastructure, many of these functions can be abstracted and shared across the enterprise as single or multiple-instantiated services. This provides a significant benefit over duplicated and non-standard implementations in that it provides a standard jumping-off point for basic functions, reducing both the time and cost of ground segment development efforts.

6.1. Timing Service

Many satellite command and control systems depend on highly accurate timing sources (for example, information transmitted as part of Global Positioning System [GPS] UHF signals). This timing service utilizes the standardized format published in

GPS interface control documentation and will make this timing functionality discoverable and consistent throughout the enterprise.

6.2. Resourcing service

One of the most critical aspects of an enterprise-wide service oriented architecture is keeping track of all resources. Information like asset availabilities, capabilities, vulnerabilities will be needed for many of the associated component services such as tasking, equipment configuration, operational reporting, and orbit analysis/visualization. The resourcing service will:

- Provide updated resource status (across the space C2 enterprise)
- Provide relevant information pertaining to all space resources
- Identify resources/units relevant to tasking request
- Allocate resources/units to selected COA

6.3. Orbital Analysis and Visualization Service

Orbital Analysis is a fundamental aspect of satellite command and control. It is used to generate ephemerides, plan maneuvers, avoid collisions, maintain a constellation and determine when a satellite will be in view of a target or ground antenna.

Nearly as important as these functions, orbital analysis tools typically provide means to visualize orbits and constellations and their relations to antennas or targets.

This "common operating picture (COP)" is necessary for planning and decision making purposes.

In a SOA, a common analysis/visualization service will interface with the resource database and operational tasking services. It can be used by the planning service, and even provide real-time visualization during operations. Finally, it can be used in the generation of data products. Ultimately, this service, in conjunction with the resourcing service, will form the basis for a space COP, available to users, planners, and decision makers across the military. Components of this overarching are identified below:

6.3.1. Orbit determination and propagation service

6.3.2. Attitude/Pointing planning service

6.3.3. Maneuver planning service

6.3.4. Collision avoidance service

6.3.5. Formation maintenance service

6.3.6. Access reporting service (both ground and space targets/antennas)

6.3.7. Visualization service

6.4. Command and Telemetry Database (look-up) Service

One aspect of satellite command and control currently driving much of the mission-unique ground system development across the DoD is inconsistent and non-interoperable spacecraft command and telemetry database implementations. Seemingly each spacecraft vendor and payload manufacturer relies on unique data typing and

formatting requirements. In turn, these requirements drive custom applications and the associated coding efforts in order to properly format and process commands and telemetry.

This service provides a command and telemetry database look-up service based on a standardized data schema. While bus and payload manufacturers will continue to have complete flexibility in defining their own commands and telemetry mnemonics, the data types and formats associated with those parameters will be constrained by a schema governed at the enterprise level. That governance enables this common service, which in turn allows the standardization of tools and applications required to interact with a mission's command and telemetry database.

6.5. Document Viewing Service

Planners, operators, analysts, and users will require the capability to view data products. This service will leverage COTS products to provide mechanisms to view and manipulate these products. Ideally, this service will span multiple operating systems and platforms (PC, Macintosh, UNIX, Windows, Linux, etc.) to give maximum flexibility to users. It will leverage the Application Programming Interfaces (APIs) inherent to the COTS products to remain compatible.

6.6. Information Assurance Service

Ensuring the security of information is inherent to military communications. Additionally, commanders want the capability to easily but securely share information

across classification domains. This service will leverage approved security controls, but do so using a web services implementation (similar to that used by the private financial sector). It will provide the following functionality

- Identification/Integrity/Avalability/Authentication/non-repudiation
- Cross domain communication, allowing for increased sharing of specified data products
- Encryption (uplink, downlink, crosslink, bulk encryption, over-the-air rekeying)

6.7. Logging service

As with any IT-centric system, logging functionality is essential to satellite command and control in order to diagnose, isolate, and ultimately resolve technical issues. This is especially important in a service oriented context, where services can be flexibly combined in an open fashion to create composite services. Sporadic performance issues are likely to be one of the most significant challenges associated with implementing a space C2 SOA, and effective logging functionality will be key to resolving them responsively.

Candidate Service Evaluations (Value Focused Thinking)

Utilizing the methodology presented in Chapter III, each of the level 1 and 2 services above was evaluated against a set of weighted criteria to assess suitability.   The results are summarized in Figure 9, and presented in detail in Table 3. The Value Focused Thinking (VFT) scoring model resulted in data sharing services being rated most

suitable, with data tasking services placing second. Real-time operations services were rated as least suitable.

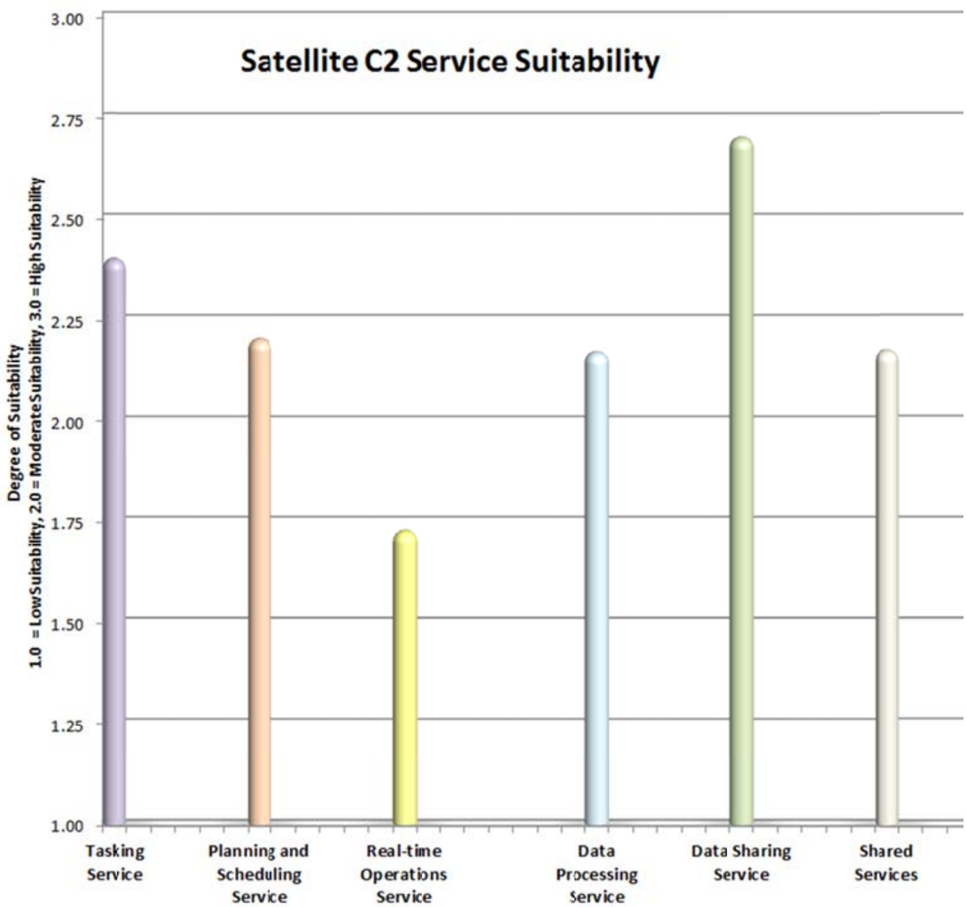

Figure 8: Satellite C2 Candidate Service Area Suitability

The assessments performed as part of this analysis were not performed on an individual mission area basis. No attempt was made, for example, to differentiate each service's suitability between the very different ISR and MILSATCOM missions. Rather, since the primary goal of SOA is to obtain commonality, re-use, and interoperability, each candidate service should be designed and assessed in the context of the worst-case requirements across the entire enterprise for a given functionality.

Table 3: Candidate Service Evaluation Matrix

Evaluation Matrix for Candidate Satellite C2 Services		Level of Support to the Mission (consistency with business/ops processes)?	Architecturally Composable (decompose into smaller or aggregate into larger services)?	Level of Commonality Across Missions	Level of Propriety (locked into vendor-specific solutions)	Criticality of Performance (QoS) Requirements	Service Value Focused Thinking (VFT) Score	Overall VFT Score
Weighting Factor:		10.0%	10.0%	30.0%	20.0%	30.0%		
Tasking Service	Tasking Parsing Service	High Suitability 3	High Suitability 3	Moderate Suitability 2	High Suitability 3	Moderate Suitability 2	2.40	2.40
	COA Development & Selection Service	High Suitability 3	High Suitability 3	Moderate Suitability 2	High Suitability 3	Moderate Suitability 2	2.40	
	Tasking Generation Service	High Suitability 3	High Suitability 3	Moderate Suitability 2	High Suitability 3	Moderate Suitability 2	2.40	
Planning and Scheduling Service	Bus Ops Planning Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	High Suitability 3	2.20	2.20
	Payload Ops Planning Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	High Suitability 3	2.20	
	Ground Segment Planning Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	High Suitability 3	2.20	
Real-time Operations Service	Ground Segment Configuration Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	Low Suitability 1	1.60	1.73
	Commanding Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	Low Suitability 1	1.60	
	Status Monitoring Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	Low Suitability 1	1.60	
	Data Storage Service	High Suitability 3	High Suitability 3	Moderate Suitability 2	High Suitability 3	Low Suitability 1	2.10	
Data Processing Service	Space Vehicle Stored Telemetry Processing Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	Low Suitability 1	1.60	2.17
	Customized Data Product Generation Service	High Suitability 3	High Suitability 3	Moderate Suitability 2	Moderate Suitability 2	Moderate Suitability 2	2.20	
	Data Playback Service	High Suitability 3	High Suitability 3	High Suitability 3	High Suitability 3	Moderate Suitability 2	2.70	
Data Sharing Service	Data Product Hosting Service	High Suitability 3	High Suitability 3	High Suitability 3	High Suitability 3	Moderate Suitability 2	2.70	2.70
	Data Product Posting Service	High Suitability 3	High Suitability 3	High Suitability 3	High Suitability 3	Moderate Suitability 2	2.70	
	Report Transmission Service	High Suitability 3	High Suitability 3	High Suitability 3	High Suitability 3	Moderate Suitability 2	2.70	
Shared Services	Timing Service	High Suitability 3	High Suitability 3	High Suitability 3	High Suitability 3	Low Suitability 1	2.40	2.17
	Resourcing Service	High Suitability 3	High Suitability 3	High Suitability 3	High Suitability 3	Low Suitability 1	2.40	
	Orbit Analysis and Visualization Service	High Suitability 3	High Suitability 3	High Suitability 3	Moderate Suitability 2	Moderate Suitability 2	2.50	
	Command and Telemetry Database (look-up) Service	High Suitability 3	High Suitability 3	Low Suitability 1	Moderate Suitability 2	Low Suitability 1	1.60	
	Document Viewing Services	High Suitability 3	Moderate Suitability 2	High Suitability 3	Moderate Suitability 2	Moderate Suitability 2	2.40	
	Information Assurance Service	High Suitability 3	Moderate Suitability 2	High Suitability 3	Moderate Suitability 2	Low Suitability 1	2.10	
	Logging Service	High Suitability 3	Moderate Suitability 2	Moderate Suitability 2	Moderate Suitability 2	Low Suitability 1	1.80	

Candidate Service Evaluation (SWOT Analysis)

In order to better qualify the VFT results described above, A SWOT analysis will be presented for the total set of candidate services, followed by a similar analysis for each service area identified in the SvcV-4.

Overall Satellite C2 SOA SWOT Analysis:

What common themes emerge across the overall set of candidate services from the analysis conducted in Tables 3-5 below?

- *Strengths:* In general, all the candidate services mapped well to actual or desired operational practices and did not introduce process inefficiencies. In some cases, they went beyond the state of current satellite C2 to realize senior leaders' vision about how the DoD can operate more effectively in space. A good example of this is the collective use of the resourcing, visualization, and data product generation service to provide operational and tactical commanders with an updated, comprehensive, and relevant Common Operating Picture. This improved battlespace awareness, combined with accurate models of asset capabilities and limitations, will enable better COA selection and more efficient tasking of space assets.
- *Weaknesses:* Mission Commonality, Levels of Propriety, and Quality of Service characteristics appear to be the criteria most significantly contributing to the weak suitability ratings of several of the candidate services. This implies that for the services that were assessed to be weak in these areas, the currently available

technology and methodologies that would be used to implement the requisite functionalities are highly unique, subject to proprietary implementations, and subject to demanding performance requirements. In regard to commonality and propriety, much of satellite C2 can be made common across mission areas, but there will always be unique requirements exclusive to a given platform or mission area (MILSATCOM, Position Navigation & Timing, ISR, Weather, etc.). Meeting these mission-unique requirements without compromising the commonality of the overarching architecture is a critical challenge that must be overcome in order to field an enterprise level satellite C2 SOA.

- *Opportunities:* What factors can help mitigate the weaknesses note above? Foremost, standards can be developed and adopted across the industry to greatly reduce proprietary implementations. By definition, SOA principles alleviate part of this problem naturally (Web Service related protocols like XML, SOAP, WSDL, and UDDI registries help reduce the need for proprietary APIs). Nevertheless, innovations like common schemas to standardize data types and formats in spacecraft command and telemetry databases can go a long way to reducing many of the cost and schedule drivers associated with ground system development efforts.
- *Threats:* The largest threat to the notion of a satellite C2 SOA is a technical community culturally, programmatically, and technologically committed to the status quo. Senior leaders have clearly articulated the need for a common, service-oriented SATOPS architecture. What remains is for strategic guidance to be translated to tangible, sufficiently funded architecting, design, and

development efforts, overcoming the organizational inertia currently present within the Space C2 community. All five commonly accepted sources of organizational inertia (26) play a role here:

- Distorted Perception
  - Myopia – According to organizational theory, the simplest source of induced myopia is turnover (26). Applied to satellite C2, if a senior leader expects to move to another organization in the near future, the weight placed on the future benefits of change may be diminished. He or she may instead focus their energy and influence on high-priority, short-term problems.

- Dulled Motivation
  - Direct Costs of Change – It is possible to look at this factor from two perspectives: the government's and the contractor's. In the case of government-led change, it is likely that change may temporarily increase the risk of failure, disrupt operations, and involve a great deal of expensive effort. Change may also imply the abandonment of costly sunk specific investments (expensive mission-unique ground systems) (26). To the contractor, a shift toward common, re-usable, and standardized ground systems can mean a very real impact to a company's profitability as less mission-unique systems are developed and fielded. In satellite C2, then, the industrial base has a clear disincentive to promote concepts like SOA.

- Failed Creative Response
    - Reactive Mind-Set – Change is inhibited when people adhere to the view that their problems are natural and inevitable (26). No one will argue that the space business is not complex or difficult. Simple logic dictates then, that high budgets and lengthy budgets (driven by arduous design/build phases and rigorous test processes) must naturally follow! It is precisely this type of thinking, however, that impedes the implementation of new paradigms to solve existing and well-known problems.
- Political Deadlocks
    - Organizational Politics – This is one of the most obvious sources of inertia. Leaders rarely act to unseat themselves or to terminate their own departments (26). In the case of Satellite C2, would an organizational realignment lead to more efficient ground system acquisition across the enterprise? What impacts would this have on individual program offices (in terms of budget and authority)?
    - Vested Values – Here individuals and departments are taken to have strong emotional or value attachments to products, policies, or ways of doing things. These vested values and interests can easily be the greatest impediments to change (26). Spacecraft builders have been creating their own spacecraft command and telemetry databases (including defining their own data types), forever. It has worked until now; why risk change?

- Action Disconnects:
  - Leadership Inaction – Although AFSPC leadership has articulated a clear vision for change, incentives have not yet been altered and relatively little direct action has been taken (to create a SATOPS enterprise program of record, for example). Until these things happen, change will be inhibited (26).
  - Embedded Routines – The life functions of an organization are its processes—its ways of doing things. Complex processes possess great inertia (26). The complicated sets of minutia comprising space acquisitions (contracting, budgeting, program management) are juggernauts in their own right.

Now that the overall strengths, weaknesses, opportunities, and threats have been identified, a lower-level analysis will be performed for each service area. Because the threat rationale discussed above in detail is applicable to each service area, the below analyses will focus only on the Strengths, Weaknesses, and Opportunities components of the SWOT model.

Tasking Services SWOT Analysis:

- *Strengths:* This functionality is well suited to be presented as a service. By its nature, the tasking service is mission-focused. It is composed of smaller services, and can be implemented in a non-proprietary fashion through the utilization of web services.

- *Weaknesses:* Because the effect each mission area provides is different, the level of commonality and therefore re-usability may be somewhat limited outside of a given mission area (it does allow, however, for extensive commonality within a mission area, e.g. MILSATCOM). Also, availability is critically important, as this service initiates the satellite C2 process. Without it, space effects cannot be achieved.
- *Opportunities:* Common data, nomenclature, and formatting standards should be implemented across the space enterprise, which will enable common tasking request language from joint force commanders, better COA selection, and standardized tasking products across a diverse set of tactical units. The use of this service by supported commands should be mandated by USSTRATCOM and the Joint Functional Component Commander-Space (the supporting component command).

Planning and Scheduling Services SWOT Analysis:

- *Strengths:* This functionality could be implemented as a service. It maps well to established operational processes, is architecturally composable, and does not rely heavily on stringent performance requirements.
- *Weaknesses:* Differences between spacecraft and payloads and the associated potential for proprietary implementations make this a functionality highly challenging to standardize. Ground equipment as currently manufactured can also be highly proprietary and customized.

- *Opportunities:* If services are defined at the appropriate level of granularity (fairly high in this case), mission-unique extensions to services can be made relatively easily without impacting other missions. This enables some degree of commonality, reusability, and interoperability, with the extensions providing the flexibility needed by individual missions. Other key enablers are the modeling services contained within the bus and payload planning services. Utilizing common data types and nomenclature for the modeling services allows this functionality to be abstracted and re-used across a wide array of spacecraft and missions (again with the appropriate mission-unique extensions as required).

Real Time Operations Services SWOT Analysis:

- *Strengths:* The real-time operations candidate services are highly consistent with operational processes and are architecturally composable.
- *Weaknesses:* The mission-unique nature of today's satellite C2 ground segments and satellites makes trying to develop a common service-oriented approach to real-time operations very difficult. Additionally, real-time operations demands high levels of capacity (bandwidth requirements are ever-increasing), availability, and reliability, meaning any SOA implementation will not be tolerant of poor QoS.
- *Opportunities:* Once again, standards (implemented and governed across the enterprise) are key enablers for providing this functionality via services. While it is unrealistic to expect every spacecraft and payload to be designed with the same commands and telemetry mnemonics, it should be possible to develop and enforce

standards with respect to data types, formats, nomenclature, etc. Another enabler of real-time operations is a common database (look-up) service for commands and telemetry. That service, discussed below, will also rely heavily on common standards.

Data Processing Services SWOT Analysis:

- *Strengths:* Potential exists to implement this functionality as services. The functionality is consistent with operational practices, is composable, and can likely be implemented by any number of COTS vendors.
- *Weaknesses:* Processing stored telemetry is hampered by the same mission-unique aspects as real-time operations. Additionally, obtaining commonality for the data product generation service may require utilizing a standardized set of COTS products.
- *Opportunities:* Similarly to real-time operations above, common data standards will greatly facilitate the development of this service by reducing the number of mission-unique extensions.

Data Sharing Services SWOT Analysis:

- *Strengths:* This functionality is highly suited for implementation as a web service, and is already fielded in numerous applications across many different sectors.
- *Weaknesses:* Though the advantages greatly outweigh the disadvantages, one cause for concern is that hosting data products and making them available to

multiple users is more complicated than a point-to-point implementation. QoS availability, reliability, and capacity requirements will need to be met.

- *Opportunities:* Shared services will be key to realizing this functionality in an effective and secure fashion. Of particular note is the document viewing service and information assurance service.

Shared Services SWOT Analysis:

- *Strengths:* The shared services in this group represent functionality that is common to multiple services. They therefore tend to be inherently common across mission areas, directly support operational practices, and can be instantiated multiple times as parts of aggregate services.
- *Weaknesses:* Common standards represent the greatest challenge posed by implementing these shared services. Additionally, because these services in many cases act as infrastructure underpinning other functionality, QoS requirements will be stringent.
- *Opportunities:* As discussed previously, common and open standards are the only way to obtain true commonality available from multiple vendors.

V. Conclusions and Recommendations

Chapter Overview

This chapter will summarize the conclusions from the analysis conducted above, characterize their significance, and will make recommendations for action based on them. Lastly it will suggest future avenues of research related to Service Oriented Architecture in satellite command and control.

Conclusions of Research

What conclusions can be drawn from the preceding analysis? First, it is clear that not all of the services identified in Chapter IV were created equal; some are better suited to immediate implementation than others. The functionalities associated with two of the areas discussed above are better suited to be presented as services in the short term: tasking and data sharing. Posting and hosting data products using web services is already ubiquitous on the internet and can be heavily leveraged since this functionality is not at all specific to the space domain. Next, the tasking service can also be considered more ready because it is inherently conducted at the enterprise (operational level); there is no need to negotiate a common standard across multiple mission areas (a weakness definitely impacting the readiness of the other candidate services).

Furthermore, both the data sharing and tasking services have only moderate performance requirements, which are primarily focused on availability/reliability, not on capacity or dealing with high data rate information streams. The proposed shared services could be developed quickly, but are likely to be dependent in the near term on proprietary solutions, and are also subject to stringent performance requirements. These

services would comprise the "infrastructure" of the architecture and must therefore have extremely high availability/reliability.

There are significant challenges associated with developing common services for mission planning, real-time operations, and data processing. The current practice of mission-unique implementations (often utilizing proprietary products) is a large contributor to this reality. Also complicating the presentation of these functions as services are the associated stringent performance requirements. These services would have to pass high quantities of information reliably, without latencies or inaccuracies. This can be challenging to do within the focused confines of a mission-unique development effort, to say nothing of an enterprise-wide common service architecture.

Nevertheless, the benefits, of SOA, as outlined in Chapter II, are potentially impactful enough that it is worth asking the question, how could the DoD make SOA work in space C2? What are the enablers that, if in place, would facilitate a shift from the current way of acquiring and employing satellite ground systems to a service-oriented model, taking advantage of the reuse, interoperability, and openness of such a paradigm? Based on the analysis above, the two most critical enablers for SOA Satellite C2 are:

- Enforced Standards
- Implementations that prioritize performance requirements

Open standards exist in the satellite C2 community (the Object Management Group's [OMG] Consultative Committee for Space Data Systems [CCSDS] specifications are a good example), but they are used only intermittently. Making matters worse, even the published standards too often try to be "all things to all people," resulting

in guidelines that are not truly prescriptive in nature. Two implementations complying with the same standard are likely to be not at all interoperable. Furthermore, industry currently has little incentive to get behind a common set of standards. Profit often centers around the development of a unique or proprietary solution to meet a given mission's specific needs. Companies subsequently tout the successful fielding of these solutions when bidding on future business, and while there is nothing inherently wrong with this, it provides a disincentive to develop an industry-wide architecture. It is important, therefore, that the standards be downward-directed and enforced—they should be contract requirements. To truly enable Service Oriented Architecture in the military satellite C2 community, standards should be developed that are prescriptive, and they must be governed by an organization that has the authority and intent to enforce them.

Next, the community must be confident that no degradation of performance will be incurred by implementing SOA. While the business case for SOA (in terms of cost and schedule) is certainly attractive, US space capabilities are far too important to the national defense to give up performance for standardization. Any SOA efforts in the Space C2 domain should place a premium on ensuring Quality of Service (QoS) requirements are identified, met, and validated as early as possible.

Significance of Research

Delivering on-orbit capabilities on time and on schedule is the DoD's highest space priority. The environment, complexity, difficulty of access, and shear technological challenge collectively make delivering space effects hard. That is precisely why, however, investigating Service Oriented Architecture for satellite C2 makes sense. On a wartime footing and in a budget-constrained environment, the DoD needs to spend its dollars on truly advancing its capabilities, not duplicating functionality within each self-contained mission area. For the sake of the warfighter and the American taxpayer, the DoD needs to rapidly arrive at a common, interoperable, open ground segment architecture, one that is able to standardize shared functionality while accommodating necessary mission-unique extensions. Service Oriented Architecture may be one of the best mechanisms available to achieve that objective.

Recommendations for Action

The Air Force Space and Missile Systems Center (SMC) should strongly consider the use of Service Oriented Architecture in its development of a compatible Satellite C2 system. Implementing a SOA not only ensures compliance with top-level DoD and Air Force guidance, but also demonstrates a commitment to open, interoperable, and reusable functionality that will ultimately mean better capabilities delivered at faster speeds. This effort should flow from the top down. Indeed, rather than allowing each mission area to continue to develop their own ground segments, SMC should realign organizationally, creating a directorate that is empowered and funded to develop, field, and govern a common Air Force satellite C2 architecture. This organization would operate in much

the same way as SMC's Launch and Range System Program Office. An enterprise architecture should be created that captures requirements for all Air Force space platforms (both existing and planned) in a single vision for an interoperable ground segment, leveraging the architecting efforts already underway by various sub-organizations within AFSPC and the DoD. The architecture should be based upon a common set of data standards, and in this effort SMC should work closely with the DoD Operationally Responsive Space office, NASA, and the NRO, who have already made advances in this area.

A formal program of record should be created to design and field the capabilities identified in the common satellite C2 architecture. This program should solicit and select candidate services from a variety of vendors, ensuring conformity with the enterprise architecture, data standards, and performance requirements. The objective time horizon for the first block of the common system should be 2020, with no competing mission-unique ground systems in development past 2015.

Recommendations for Future Research

This thesis primarily focused on a functional analysis of what services would be suitable for a Space C2 SOA. While it recognized the need to address service performance requirements, common standards, and the actual technical design of space C2 services, these efforts were left to future researchers. In particular, the development of common standards and clear-cut performance requirements are pre-requisites that must be completed before real technical service design can begin in earnest.

Further architecting work is also required. A logical data model (DIV-2) for a satellite C2 SOA should be created prior to service design, along with an OV-2 identifying organizational need lines. These viewpoints will help identify the data flows in and out of the web services, and those will be the providers/consumers of the services.

Summary

At first glance, the DoD and the Air Force have been speaking with one voice with respect to both Service Oriented Architecture and Satellite C2 for some time. The guidance from senior leadership on SOA "goodness" is unequivocal, and most experts would agree it is in the Air Force's best interest to adopt a shared, interoperable approach to satellite operations as quickly as possible. Why then, in late 2010, is there still no clear path to achieving a common, service-oriented ground architecture?

The analysis conducted in this thesis concluded that certain functionalities are more ready to be presented as services than others: namely tasking and data sharing. Due to a lack of agreed-upon data standards that can span mission areas and concerns about the ability of SOA to meet stringent performance requirements, other space C2 functions are currently less suited to service implementation. Nevertheless, if these last two enablers can be put in place, the Air Force and the DoD stand to reap significant cost and schedule benefits stemming from re-use and shortened developments. Indeed, the potential rewards alone make the construction of an enterprise-wide Satellite C2 Service Oriented Architecture worthy of focused study and consideration at the highest levels of the Air Force and the DoD.

Appendix A: Acronyms

AF	Air Force
AFSPC	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
AMMOS	Advanced Multi-Mission Operations System
API	Application Programming Interface
C2	Command and Control
CCSDS	Consultative Committee for Space Data Systems
CIO	Chief Information Officer
COA	Course of Action
COP	Common Operating Picture
CORBA	Common Object Request Broker Architecture
COTS	Commercial Off-The-Shelf
CRUD	Create, Read, Update, and Delete
DCOM	Distributed Component Object Model
DISA	Deep Space Information Services Architecture
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DSN	Deep Space Network
GIG	Global Information Grid
GMSEC	GSFC Mission Services Evolution Center
GPS	Global Positioning System
GSA	Ground System Architecture
GSAW	Ground System Architectures Workshop
GSFC	Goddard Space Flight Center
HTTP	HyperText Transport Protocol
HW	Hardware
IDL	Interface Definition Language

ISR	Intelligence, Surveillance, & Reconnaissance
IT	Information Technology
JFC	Joint Force Commander
JPL	Jet Propulsion Laboratory
MILSATCOM	Military Satellite Communications
MMSOC	Multi-Mission Satellite Operations Center
MPCS	Mission data Processing and Control Subsystem
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
OMG	Object Management Group
OO	Object Orientation
OPREP	Operational Report
OPSCAP	Operational Capability
ORB	Object Request Broker
ORS	Operationally Responsive Space
PMO	Program Management Office
QoS	Quality of Service
R&D	Research & Development
RPC	Remote Procedure Call
SATOPS	Satellite Operations
SMC	Space and Missile Systems Center
SOA	Service Oriented Architecture
SOC	Satellite Operation Center
SOAP	Simple Object Access Protocol
SPO	System Program Office
SW	Software
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UDDI	Universal Description, Discovery, and Integration
UHF	Ultra-High Frequency

US	United States
USAF	United States Air Force
VFT	Value Focused Thinking
W3C	World Wide Web Consortium
WSDL	Web Services Description Language
XML	eXtensible Markup Language

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14. ABSTRACT

The mission-unique model that has dominated the DoD satellite Command and Control community is costly and inefficient. It requires repeatedly "reinventing" established common C2 components for each program, unnecessarily inflating budgets and delivery schedules. The effective utilization of standards is scarce, and proprietary, non-open solutions are commonplace. IT professionals have trumpeted Service Oriented Architectures (SOAs) as the solution to large enterprise situations where multiple, functionally redundant but non-compatible information systems create large recurring development, test, maintenance, and tech refresh costs. This thesis describes the current state of Service Oriented Architectures as related to satellite operations and presents a functional analysis used to classify a set of generic C2 services. By assessing the candidate services' suitability through a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, several C2 functionalities are shown to be more ready than others to be presented as services in the short term. Lastly, key enablers are identified, pinpointing the necessary steps for a full and complete transition from the paradigm of costly mission-unique implementations to the common, interoperable, and reusable space C2 SOA called for by DoD senior leaders.

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